Optimisation of Operational Modes of Short-Route Hybrid Ferry: A Life Cycle Assessment Case Study

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ABSTRACT: Owing to high operation cost of traditional power systems and serious environmental situation, the usage of hybrid power system on board is increasingly attracting attentions. Applying life cycle assessment (LCA) approach, the key objective of this paper is to evaluate and optimise the operational modes of hybrid power system for a short-route ferry in Scotland. The applied hybrid system is mainly comprised of generators and lithium ion batteries and there are four operational modes based on the power requirements during voyages. To carry out this study, a top-bottom design strategy is applied to build up the short route ferry with hybrid power system in GaBi. The cradle to grave of the ferry is modelled referring to a practical ship life: construction, operation, maintenance and dismantling. In order to determine the optimal power distribution and minimal emissions, a series of operation profile cases with different power distributions were investigated for a certain route with following operational phases: transiting, manoeuvring and at slip. The comparison results from different voyage phases indicated the optimal power distribution between gen-sets and batteries with minimised operation costs. The environmental assessments for each case were carried out in order to identify the relationship between power distributions and emissions. The study concluded that there are significant impacts on the energy consumption and environment during the life cycle of a hybrid power system and therefore it is essential to apply appropriate operation optimisation on the system.

1 INTRODUCTION

Environment protection has become one of the most popular topics in this century because of the significant impacts of global warming and pollutions. Although more and more researches and projects are striving to mitigate or reduce the impacts, environment protection is still one of the most important tasks for contemporary society. One reason of this situation is that applying novel technologies or theories may have an effect to other processes. As a result, the net impact of mitigation or reduction is not so significant. To have a comprehensive view on the mitigation and reduction results, LCA concept is introduced which will consider and analyse the whole life of a product. LCA can help indicate the costs and environment impacts of products in their life cycle. The indication can be used for further decision making processes which provide suggestions for companies, societies and even governments. There are many different commercial LCA software available in the market. This paper presents a review on commercial LCA software and the evaluations on the preferred candidates by indicating their advantages and disadvantages. This paper will also make a contribution to the development of LCCA software by recommending and constructing a preliminary software structure.

2 LCA METHODOLOGY

Life cycle assessment is a technique to evaluate the environmental impact of products considering from cradle to grave stages and decisions could be made based on the assessment in order to minimise the environment impacts of the products. According to ISO standard 14040 (2006) and 14044 (2006), there are four phases in an LCA study: a) the goal and scope definition phase, b) the inventory analysis phase, c) the impact assessment phase, and d) the interpretation phase. For a life cycle modelling, the basic framework is presented in the following. Currently, there are many different LCA software available and most of them are commercial software, like GaBi, KCL-ECO, LCAiT, PEMS, SimaPro, and TEAM. These software not only provide software package but also database. Researchers have evaluated these software based on their characteristics.

Evaluation results of some LCA software are presented in the followings

Table 1.

Among these LCA software, GaBi is commonly used with a comprehensive database for many different industries. In this paper the LCA carried out using GaBi. GaBi was applied by Jouni et al (2017) to assess the environmental impact of municipal solid waste management in Hangzhou, China with mechanical treatment of waste and incineration incorporated. The results showed that the application of waste management can reduce up to 33% of global warming potential in the city. Esteve-Turrillas & Guardia (2017) conducted a life cycle assessment using GaBi to compare the recovered cotton from recycled garments with cotton from traditional and organic crops. The research illustrated the organic cotton cultivation has a positive impact on environment protection which avoids using pesticides or chemicals but still have some pollution from ginning and dyeing processes just like traditional cultivation. However, the cotton recover process does not involve any of these processes (insecticidal, ginning or dyeing process) which means it is a much more environment friendly process. Another LCA on alkaline hydrogen fuel cell is carried out by Benjamin et al (2013) aiming to find the impact of using gas atomised sponge nickel instead of cast and crush sponge nickel and platinum. Rodrigo et al (2017) applied LCA method to evaluate the carbon footprint during local visitors' travelling in Brazil. A case study of route from Rio de Janeiro to Sao Paulo was conducted and also as a result of using bio-fuel, the study indicated the most carbon efficient travel mode is overland public transportation.

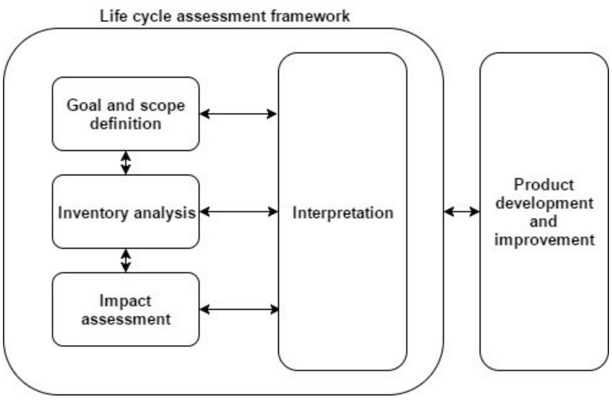

Figure 1 Stages of an LCA model

In ship building industry, LCA is also applied in order to determine the environmental impact and cost investment. Eduardo & Peilin (2014, 2016) investigated the environmental impact of two different hull paintings and three types of ballast water treatment systems with their cost assessment. With LCA model, the impacts from different scenarios were determined which recommended the ship builder and ship owner the best option considering both cost and environment assessments. Ling-Chin et al (2016) applied LCA method and conducted a case study to evaluate the benefit of installation of a hybrid power system on a Ro-Ro vessel. They concluded that the life cycle of a new-build hybrid power system was imperative which would help determine the significant impact on the environment, human beings and natural reserves so that proper decision and consideration can be made.

Table 1 Evaluation results of LCA software for product and process (Dašić et al., 2007)

Characteristics	GaBi	Sima Pro	Team
Functionality	5	2	4
Flexibility	3	3	4
Database	4	4	5
User-friendless	5	2	3
Software properties	3	3	2
Service	5	3	5
Cost	4	5	2

Note: The evaluation ranges from 1 (very negative) to 5 (very positive).

3 LCA MODEL ESTABLISHMENT AND MODIFICATIONS

3.1 *Common modules*

There are built-in models for transportation means and fuels in GaBi. To simplify model, the emissions from these processes are filtered and selected according to Table 2 in order to consider these significant emissions. All the models presents in the case study are derived and modified from GaBi built-in models with the considerations of these significant emissions. Emissions with significant impact in global warming (GWP), acidification (AP), eutrophication (EP) and photochemical ozone creation potential (POCP) are selected and analyzed in this paper. Table 2 presents the consideration of emissions with their characterization factors under different pollution categories. Three other built-in models are developed to present the relevant data and processes in the LCA modelling: fuel, transportation and scrapping. A template fuel model is developed for diesel oil and presented in Table 3 which listed the emissions from the production of diesel oil and supplied to refilling stations. To complete the modelling, fuel model for heavy fuel oil, lubricants and nature gases are developed based on this template. For transportation model, a template model for trucks is developed which indicates the fuel consumption and emission released due to specific transportation distance and truck load. During the analysis, only one truck model was used which has 3.3t payload. The template of energy required from scrapping processes are presented in Table 4 which indicates the quantities of energy for each kilogram of different material scrapping.

Table 2 Emission types considerations for different impact categories in GaBi model

Emission	GWP	AP	EP	POCP
CO_2	1	×	×	×
CO	0.027	×	×	×
CH_4	25	×	×	0.006
Dinitrogen oxide	298	×	0.27	×
SO_2	×	1.2	×	0.048
NO_x	×	0.5	0.13	0.028
HCL	×	0.749	×	×
NH_3 [to water]	×	×	0.35	×
NH_3 [to air]	×	1.6	0.35	×
PO_4 [to fresh water]	×	×	1	×
COD [to water]	×	×	0.022	×
C_2H_4	×	×	×	1
C_2H_6	×	×	×	0.123
C_7H_8	×	×	×	0.637

Table 3 Quantities of emissions from different type of fuel

Emission category	Quantity of emission (kg)	
	Diesel	Truck
CO_2	4.00E-01	0.005228
CO	5.75E-04	4.58E-06
CH_4	4.08E-03	3.48E-09
Dinitrogen monoxide	0.00E+00	0
SO_2	1.29E-03	3.29E-08
NOx	1.20E-03	2.2E-06
HCL	4.08E-06	0
NH_3 [to fresh water]	2.13E-07	0
NH_3 [to sea water]	2.92E-16	0
NH_3 [to air]	1.43E-04	2.04E-08
PO_4 [to fresh water]	4.83E-05	0
COD [to sea water]	3.42E-05	0
COD [to fresh water]	2.23E-04	0
C_2H_4	2.05E-04	0
C_2H_6	8.68E-10	0
C_7H_8	1.60E-07	0

3.2 *Construction*

The ship construction phase is to build, assemble and install all the selected materials and machinery from the early design stage and also to deliver new ship to ship owner who will run the shipping business. For ship hull and superstructure, materials like steel plates, aluminium panels and stainless steel frameworks will be purchased, cut, bended, welded and coated as part of ship construction, and machinery such as main engines, boilers, and propellers, will be transported and installed to the new ship after their purchases. For this case study, consideration of ship construction phase is simplified which focuses on the main engines. It is because the focus of this case study is to evaluate the effectiveness of three different engine configurations: diesel mechanical (DM) system, diesel electrical (DE) system and hybrid system. The evaluations of construction phase will include the environmental analysis and cost assessment from the purchase of the main engines and batteries to the installation. The model was built with GaBi and presented in Figure 2 and Figure 3.

Table 4 Energy required for scrapping

Item	Energy (MJ)	
	Electricity	Natural gas
Iron & Steel	1.71	0.62
Stainless steel	7.18	2.6
Al	0.1	10.22
Cu	-	-
Zn	0.73	0.34
Pb	-	-
Ni	1.92	2.3

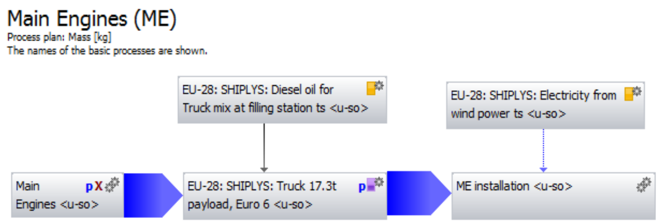

Figure 2 Machinery construction processes for engine

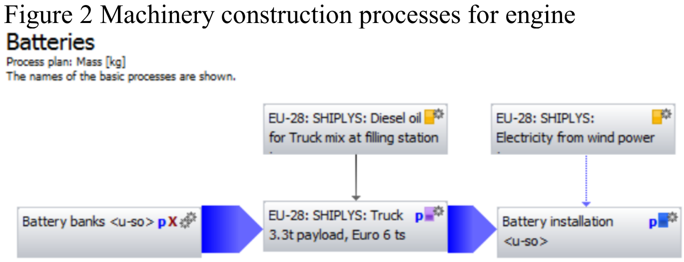

Figure 3 Machinery construction processes for Battery

This figure indicates the processes and also the boundaries of the assessment which starts from purchases and then transported and installed to a ship. The energy consumptions are also considered: fuel consumption of transportation and electricity for installation. The boundaries of the environmental assessment is set to include the emissions from energy consumptions as well as the production of energy. For example, the diesel oil was used for truck which was supplied by filling station. However, in a supply chain of a filling station product, there are several processes: well drilling, crude oil production and processing, transportation of crude oil via pipeline resp. vessel to the refinery as well as transportation from refinery to filling station (GaBi). To simplify the construction model, the costs before filling station are not considered as they are difficult to gather these data and will have little impact on final results. However, the emissions due to these processes are available so that the environment impacts of the supply chain are considered in the analysis.

3.3 *Operation*

According to voyage reports, the current operational frequency of the case ship is approximately 20 trips daily from Sconser to Raasay in North Scotland at an average speed of 9 knots. A series of operation profile cases with different power distributions are investigated for this route with following operational phases: transiting, manoeuvring, at slip and in port. In addition, the daily hours of operation can be allocated to 6 hours for transiting, 0.6 hours for manoeuvring, 3.72 hours at slip and 13.68 hours in port. The ship has a regular voyage schedule, but it takes 52 days of maintenance and vacation annually, leading to 313 working days a year. The study also estimated that the case ship will continue to participate in this regular schedule for a lifetime of 30 years before being dismantled.

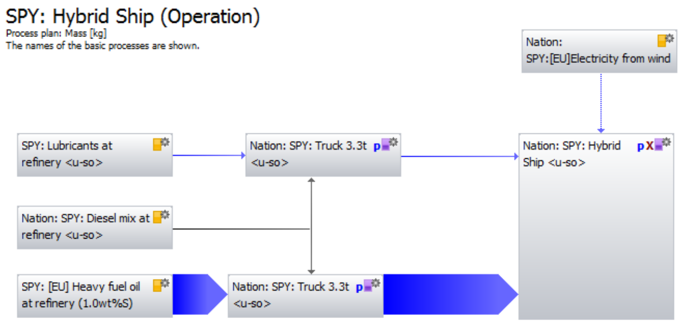

Figure 4 Operation model for hybrid system

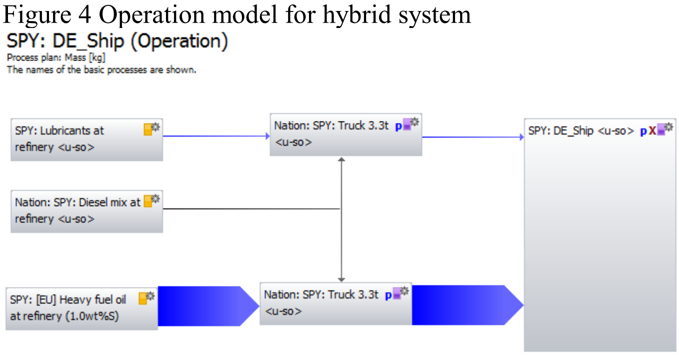

Figure 5 Operation model for DE system

The process and boundary of the analysis outlined were transformed into a module as shown in Figure 4 and Figure 5.The process begins with production of the fuel and lubricants at refinery and ends by burning them onboard while the initial production of the crude oil at reservoir and its transportation to the refinery are not considered. In this process, the flows of energy and emissions are tracked for LCA and the cash flow was monitored for LCC. It was assumed the fuel and lubricant are supplied from Kinneil Terminal BP which is about 230 miles away from the Sconser. In the case ship, as a conventional benchmark, marine diesel oil (MDO) with Sulphur content 1.0% was assumed to be used in the main engines. For LCCA, fuel prices are determined as below. In addition, the costs of industrial electricity generated from wind power was assumed to be 0.07Euro/kWh night charging prices according to Scotland electricity price information (Scottish power, 2015).

- MDO price = 290.58 Euro / ton
- Lubricant price = 1681 Euro / ton
- Electricity costs (night time) = 0.07Euro/kWh

In any year, the load on the engine depends on the operating model, and the sum of the annual fuel consumption is the consumption of time spent in each operating mode as expressed in Eq. (1).

$$F = \sum_{i=1}^{n} FS_i \cdot P_i \cdot T_i \tag{1}$$

FS_i specific fuel consumption as a function of engine load
P_i engine load for each engine load
T_i Time spent in each operating mode

$$L = \sum_{i=1}^{n} LS \cdot P_i \cdot T_i \tag{2}$$

LS specific lubricant consumption

$$C_F = \sum_{i=1}^{n} \text{€}_{fc} \cdot FS_i \cdot P_i \cdot T_i = \text{€}_{fc} \cdot F \tag{3}$$

€_{fc} fuel price

$$C_L = \sum_{i=1}^{n} \text{€}_{lc} \cdot LS \cdot P_i \cdot T_i = \text{€}_{lc} \cdot L \tag{4}$$

€_{lc} lubricant price

Table 5 Operational profile of case ship.

	Category	9 knots	Man.	Slip	Port
	Daily operation hours	6	0.6	3.72	13.68
	Propulsion power (kW)	322	144	87	0
Hybrid	No. of Engines	1	0	0	0
	Load (%)	89	0	0	0
	SFOC (g/kWh)	212.6	0.0	0.0	0
	Fuel cons. (g/day)	4.11E+5	0	0	0
	LO cons. (g/day)	3.9E+5	0	0	0
	Elec. (kWh/day)	0	86.4	324.0	0
DE	Num. of Engines	1	1	1	0
	Load (%)	89%	40%	24%	0
	SFOC (g/kWh)	212.6	240.8	266.9	0
	Fuel cons. (g/day)	4.11E+5	2.08E+4	8.64E+4	0
	LO cons. (g/day)	3.9E+5	1.8E+4	6.6E+4	0
DM	Num. of Engines	2	2	2	0
	Load (%)	32%	14%	9%	0
	SFOC (g/kWh)	252.4	287.1	300.5	0
	Fuel cons. (g/day)	4.41E+5	2.24E+4	8.72E+4	0
	LO cons. (g/day)	1.1E+3	5.1E+1	1.9E+2	0

The operating principle of a hybrid ship is that the battery is charged by shore electric power overnight in port. The charged battery is used during maneuvering and at slip in replace of diesel generators while diesel generator is only running for transiting. On the other hand, for DE, single generator is running all operation modes while for DM two main engines should run all operation modes. The proposed operational profile for the case ship was determined as shown in Table 5. Its propulsion power was estimated from the shipyard based on their previous ship building records. The fuel consumption and emissions are quantified in three different modes. The emission specifications are derived from the published literature (Carlton et al, 1995; Alkaner and Zhou, 2006).

Table 6 Emission factors for engine operation

Engine Emission	Fuel based factor*(tonnes /fuel-ton)
NOx	0.057
CO	0.0074
CH4	0.0024
CO2	3.170
SOx	0.02 (=20×(1.0)%S content)

**Carlton et al, 1995; Alkaner and Zhou, 2006*

3.4 *Maintenance*

The structure of the marine engine consists of several parts and it is necessary to carry out regular maintenance work as planned to confirm that it works smoothly. A daily inspection is performed according to the instructions of the engine manufacturer as well as various uptime based maintenance such as 200 up to 100,000 hours. Table 7 indicates the periodical maintenance schedule specified by the manufacturer. The LCC for maintenance is carried out based on the engine operating time during its lifetime. Figure 6 shows the relationship between the engine operating time and the driving year while the total costs for engine maintenance over time is presented in Figure 7. The environmental impacts associated with the production and transport of marine engine spare parts during the maintenance phase were not considered because the range of environmental impacts at this stage is relatively small compared to other stages and there is a limit to the LCA for maintenance with uncertainties.

According to the ship voyage schedules and operating profiles, estimated engine running hours annually can be drawn as shown in Figure 6. For hybrid systems engines running hours are reduced because batteries are replacing the generators during maneuvering and at slip. According to the vessel's voyage schedule and operating profile, the annual engine run time can be plotted as shown in Figure 6. For hybrid system engines, the running time is reduced as taking advantage of using the batteries instead of generators during maneuvering and at slip. The operating time for each engine in DE and DM is the same. However, maintenance intervals for DM are doubled because two engines must always run for DM. As a result, DM maintenance costs are relatively high and hybrids are relatively low as shown in Figure 7.

3.5 *Scrapping*

The scrapping of a ship covers docking, disassembling, transportation and treatments for an end of life ship. For iron scrapping as an example, it will go through the following processes: collection, sorting and analysis, processing (shredder processing, dezincification treatment and briquette processing) and shipping to steeling maker or casting maker. Through these processes, parts of iron will be recycled for making steel and cast iron and the others will be disposal such as land fill and incineration. As this case study focuses on the main engine, the scrapping of main engine will be indicated, modelled and analyzed in GaBi and the model is presented in Figure 8. The evaluation of main engine scrapping starts from end of life ship where the engine is disassembled. Then the engine will be transported for scrapping and recycling after disassembling the different materials from the main engine.

Table 7 Engine maintenance profiles.

Interval (hours)	Working time (hours)	Spares to be renewed	Spare costs (% engine costs)
Daily	0.4	-	-
200	2.75	-	-
400	4.20	- Oil changes	0.09 %
1,200	0.50	- spin on oil filter - seal ring - etc.	1.67 %
4,000	1.30	-	-
6,000	4.00	- v-belt - injection nozzle - etc.	5.29 %
10,000	30	- Repair kit - Rubber hose - etc.	49.21 %
20,000	40	- Connecting rod bearing - Keystone ring - etc.	20.75 %
40,000	70	- Pistons - Crankshaft bearings - etc.	47.4 %

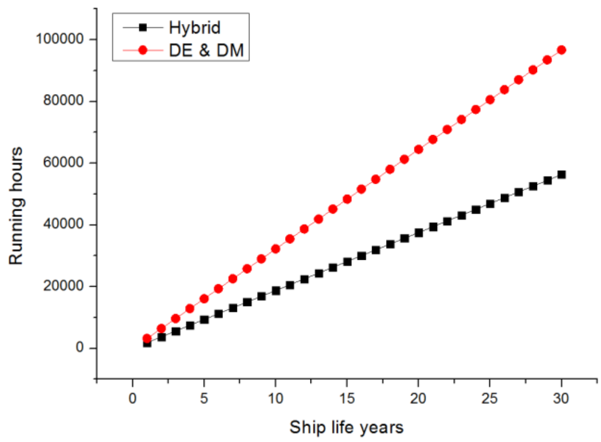

Figure 6 Running hours or each engine vs operation years

Table 8 presents data about the contents of an engine and these materials will be considered in the scrapping model of ship life cycle analysis model.

According to this table, steel and cast iron occupy the most of the mass of a main engine and other materials like aluminum, copper, zinc, lead and nickel only take small portion of mass. The energy required and emission released from scrapping processes are presented in Table 8 which indicates the amounts for each kilogram material scrapping. The cost information for scrapping phase is also listed in Table 8. With these tables, the energy required and emission released can be derived using GaBi LCA model.

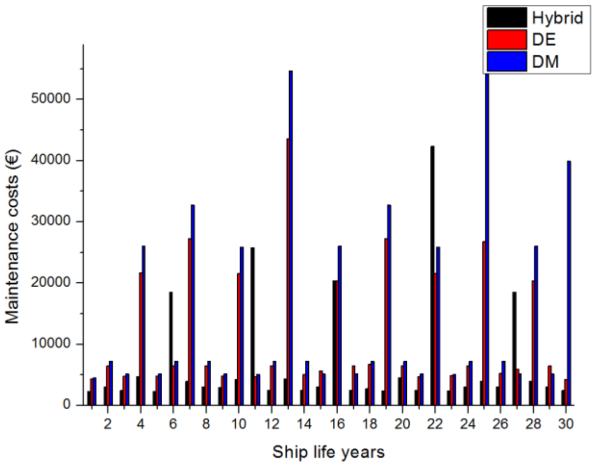

Figure 7 Engine maintenance costs over ship life years

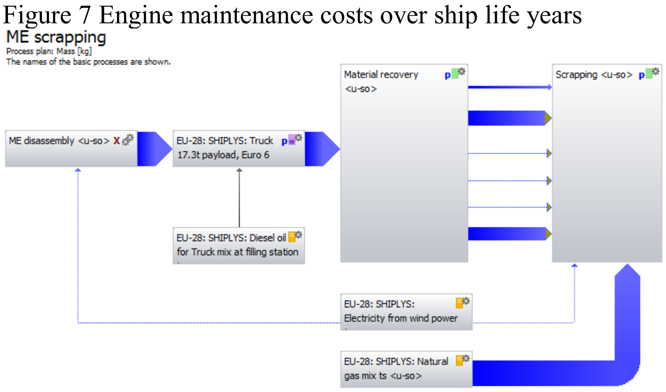

Figure 8 Engine scrapping processes

Table 8 Material content of main engine

Engine Material	Ratio	360kW	450 kW	Recycle
	(Weight %)	(3.2 t)	(4 t)	
Steel	40	1.28	1.6	Recycled
Cast iron	46	1.472	1.84	30%
Aluminum	8	0.256	0.32	Recycled
Copper, Bronze, Brass, Zinc	0.2	0.0064	0.008	
Lead	0.1	0.0032	0.004	
Plastic	0.9	0.0288	0.036	
Rubber	0.9	0.0288	0.036	
Paints	0.9	0.0288	0.036	Waste
Oils and Grease	3.0	0.096	0.12	Waste
Total	100	3.2	4.0	

4 CASE STUDY

In this section, we have applied the philosophy of LCA and LCCA discussed in the previous section to a case study that examines the performance of hybrid vessels in terms of cost and environment.

Table 9 Specification of case ship

L x B x D	39.99 m x 12.2 m x 1.73 m		
Displacement (t)	100 tons (Steel)		
Engine configuration	Hybrid (Actual)	DE	DM
	360 kW x 3 sets (3.2 tons) + 350 kW lithium-ion battery x 2 sets	360 kW x 3 sets (3.2 tons)	450 kW x 2 sets (4 tons = 8.88 kg/kwh)

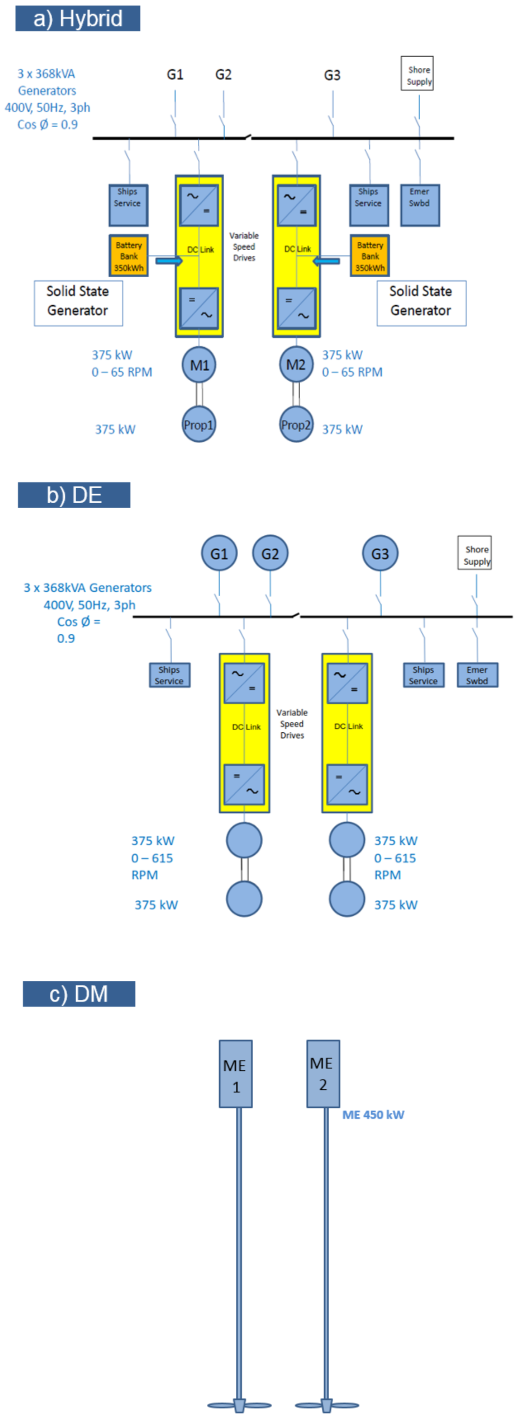

Figure 9 Layout of different engine configurations

4.1 *Goal and scope definition*

MV Hallaig, a hybrid Ro-Pax ferry, was selected as a case ship and the existing propulsion system DE and

DM were applied to virtually identical vessels. The specification of case ship is shown in Table 9.
The goal and scope of case study was defined to examine the benefits of hybrid systems compared to other existing vessel types - diesel electric (DE) and DM (DM) propulsion systems - in terms of life cycle cost and environmental impact (Figure 9). Regarding the purpose of study, the scope of this study is limited, thereby the module is selected for propulsion systems at each life cycle stages.

4.2 *Impact assessment*

4.2.1 *LCA*

As a result of evaluating the impact on the environment from the life cycle of the ship as shown in Figure 10, it was shown that the operation phase is expected to generate a relatively large amount of pollutants compared to other three phases. It reveals that alternative cases are preferable to base case. This is because the environmental impact is relatively smaller than that of the base case.

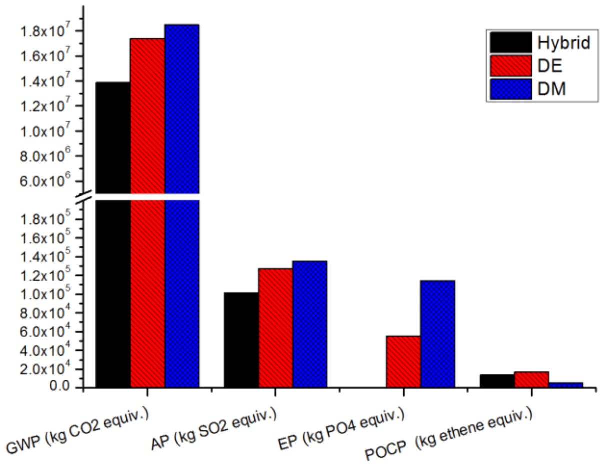

Figure 10 Results of LCA

4.2.2 *LCCA*

Determining the costs is challenging because of the time value of money, money in the present is worth more than the same amount in the future. This is both because of earnings that could potentially be made using the money during the intervening time and because of inflation. The discount rate element of the net present value (NPV) formula is a way to account for this. In this principle; this case study applies PV to investigate the cash flows during the whole life of a ship. The NPV formula is presented as following:

$$NPV=\sum_{t=1}^{T}\frac{C_t}{(1+r)^t}-C_0 \qquad (5)$$

Where:

C_t Opex: net cash inflow during the period t
C_0 Capex: total initial investment costs
r discount rate, and
t number of time periods (years).

Table 10 LCCA for three engine configurations

Case	Phase	Cost *(K=1,000 Euro)*
Hybrid	Construction	106K*
	Operation	1,390K
	Maintenance	203K
	Scrapping	18K
	Total	1,718K
DE	Construction	89K
	Operation	1,435K
	Maintenance	347K
	Scrapping	12K
	Total	1,885K
DM	Construction	74K
	Operation	1,523K
	Maintenance.	930K
	Scrapping	9K
	Total	2,536K

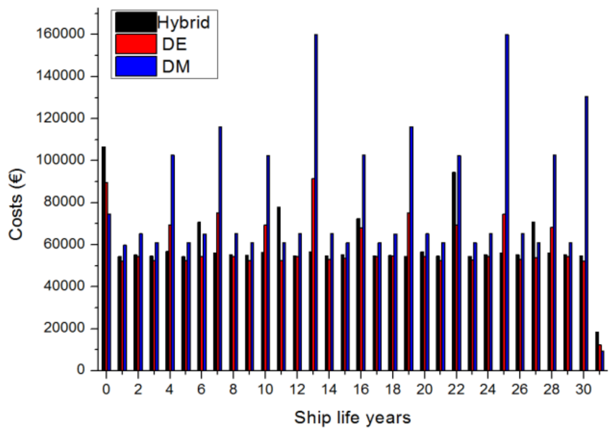

Figure 11 Cost distribution over ship life years

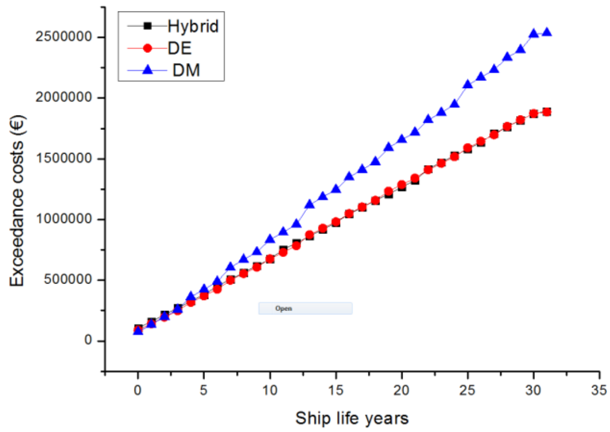

Figure 12 Exceedance Cost over ship life years (without considering discount rate)

The results of LCCA are shown in Table 10, Figure 11 and Figure 12. In the same line with the LCA, it shows that the alternative case is more profitable as the costs of ships' life cycle is relatively smaller than the base case. This table shows the benefit of approximately € 170,000 obtained when DE is applied to the case ship. The benefit can be maximum compared to DM it will be approximately € 818,000 over the life span of the ship.

4.3 *Parametric analysis*

As the history of hybrid ships is short, the investigations on optimized operational conditions are necessary. This parametric analysis is a generic approach to investigate the influence of the uncertainties.

First, this assumes that hybrid systems are recharged in different principles. As stated earlier, it practices to charge the batteries overnight from shore supply and it uses for berthing and manoeuvring operations only. However, the ship has several other options as below.

- Case 1: Batteries charges by on-board diesel engines overnight
- Case 2: Batteries fully charged by shore supply and supplement the transient operation

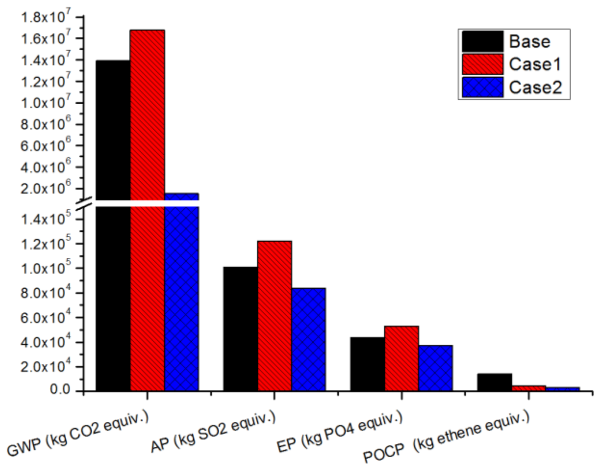

Figure 13 Results of LCA for parametric analysis

Case 1 describes one possible operational scenario that batteries are being charged by on-board diesel engines rather than being provided electricity from shore. The charged batteries are used for berthing and maneuvering only. Meanwhile, Case 2 presents the maximum use of batteries; another possible scenario that batteries are fully charged by shore supply and used for berthing and manoeuvring. However, remaining battery power (equivalent to cover one hour transient operation a day) is used for transient phase as well. The results are compared as below in Figure 13 and Figure 14.The results show that Case 2 where the batteries are used maximum produce less emissions than other two scenarios. From this, we could demonstrate that using batteries are cleaner option than conventional engine operations. This section is to investigate the operational phases to feature the different operational conditions. As hybrid engine can be charged / operated in different conditions, it may be necessary to investigate the ways to maximize its benefits. To achieve this, parametric analysis was carried out.

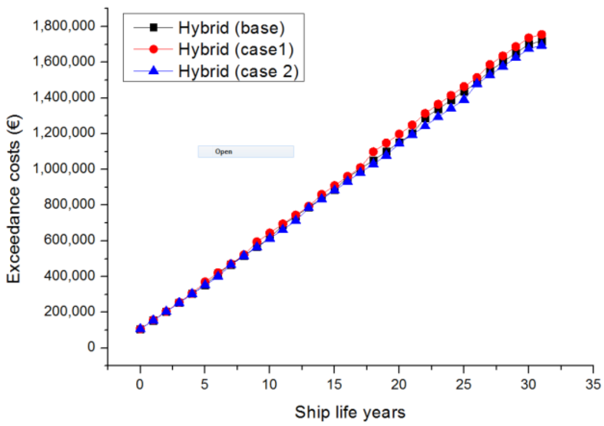

Figure 14 Exceedance Cost over ship life years (without considering discount rate)

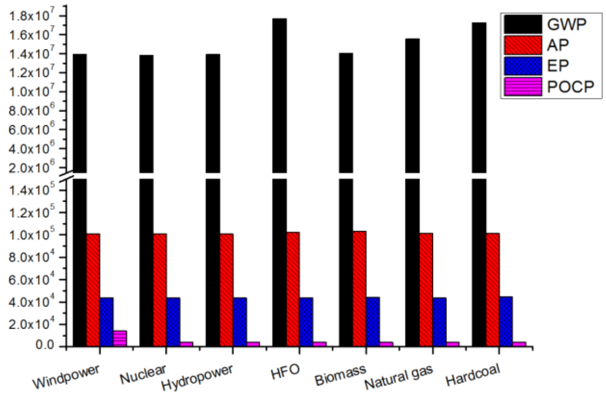

Figure 15 Results of LCA

In terms of LCCA, the cost differences are not remarkable although Case 2 is slightly more beneficial than other options. Meanwhile, it may arose a question that electricity is produced by a variety of sources. It may be true that different process and energy sources for electricity production results in different level of environmental impact. This paper initially assumed that electricity provide to the hybrid is generated from wind power. To investigate the impact of this uncertainty, this section investigates six other representative electricity production: Nuclear, hydropower, heavy fuel oil (HFO), biomass, natural gas and hard coal. The result of LCA analysis can be shown as below in Figure 15. Regarding GWP, not surprisingly, conventional fossil fuels are relatively highly-contributing to environment compared to renewable and other cleaner energy sources. The result addresses us that the application of hybrid system is important. However, the source of electricity how it is generated is also important parameter for us to sustain the planet cleaner entirely.

5 CONCLUSIONS

This paper investigated the costs and environment impacts of applying hybrid propulsion system comparing with DM and DE systems. The advantages of applying hybrid system (battery system) are derived from the investigation and presented in this paper. One of the advantages might be interesting to shipowners is that the life cycle cost with hybrid system application is the lowest among three options. To meet the main stream of environmental protection, the emissions released in the ship life span are considered and the results indicates that the hybrid system can be considered as a green ship technology due to the using of power from batteries which are eventually charged from renewable power plants. This case study also illustrated that life cycle assessment, including both life cycle cost assessment and environmental analysis, provides a comprehensive evaluation on products (ship in this paper) from cradle to grave and also provides recommendation on an optimized option. To improve the feasibility and accuracy of LCA results, further work is still necessary because there are some estimations and assumptions prior to the case study which may impact the results. Therefore it is always suggested to derive realistic data to carry out a detailed and precise life cycle analysis.

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